# Power Production with Zero Atmospheric Emissions for the 21st Century

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# POWER PRODUCTION WITH ZERO ATMOSPHERIC EMISSIONS FOR THE 21ST CENTURY

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## ABSTRACT

This paper describes a new concept for economically producing power without atmospheric emissions of regulated or greenhouse gases. A 5-MW to 10-MW experimental electric power generating plant is being designed for installation at the Lawrence Livermore National Laboratory to perform research to develop the new technology and to demonstrate its reliability.

The research electric power generating plant will burn any gaseous fuel, including syngas derived from coal, with oxygen. Natural gas and oxygen will be used initially to produce a mixture of steam and carbon dioxide. The mixture will be delivered to three turbines in series to produce electricity. After leaving the low-pressure turbine, the gaseous mixture will be cooled in a condenser where the carbon dioxide separates from the steam. The carbon dioxide will be pumped into a local oil formation, which is located at a depth of 460 m below ground adjacent to the Laboratory. In the more general siting case, the carbon dioxide would be pumped into deep underground permeable strata.

The natural gas will be combusted with oxygen in a gas generator to produce the turbine working fluid. Three turbines will drive an electric generator to generate electricity. In the first phase of the research, the plant will use three commercially available steam turbines that operate at a temperature of 566°C.

In a second phase, the high- and low-pressure turbines will be replaced by turbines using uncooled blade technology developed by the U.S. Department of Energy (DOE) to permit a turbine operation temperature of 816°C. The intermediate turbine will use actively cooled gas turbine technology and operate at a temperature of 1425°C. This plant will have an efficiency of 50%. DOE has funded research to reduce the cost of oxygen generation using ceramic membranes. When this technology becomes available and when high-temperature steam turbines are developed, efficiencies of 60% are expected, including the energy cost of carbon dioxide sequestration.

Economic studies indicate that the cost penalty for sequestering the carbon dioxide of the research plant will be approximately 4%, when using the second-phase technology, making it one of the lowest-cost options for sequestration of greenhouse gases from a power plant. A similar cost penalty applies to plants with outputs ranging from 100 to 400 MW.

## INTRODUCTION

Production of electric power with zero atmospheric emissions is one of the goals of DOE's Vision 21 Program. [1][2] One decade ago, such a concept would not have been considered to be viable. However, in recent years a number of technical publications [2-9] have appeared that address this concept. This paper describes a 5-MW to 10-MW research electric power generating plant that has been proposed to the U.S. Department of Energy's National Energy Technologies Laboratory Fossil Energy Program. The plant will be installed at the Lawrence Livermore National Laboratory in California, U.S.A., to perform research to produce electric power with zero atmospheric emissions.

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The plant will use a Rankine cycle to drive three turbines connected in series. However, unlike conventional steam power plants, the research plant will not use a boiler to generate steam. Use of a boiler presents two disadvantages to the efficiency of the Rankine cycle. First, the maximum cycle temperature is limited by the maximum metal temperature that boiler components can withstand; and second, a substantial amount of the heat in the fuel is lost by the exhaust gases that are vented to the atmosphere.

The turbine working fluid is produced in a gas generator by the stoichiometric combustion of natural gas and oxygen. Hence, the maximum operating temperature of the Rankine cycle is no longer controlled by the maximum operating temperature of a boiler. Rather, the maximum operating temperature of the turbines becomes the efficiency-limiting temperature. The hydrocarbon fuel does not need to be natural gas but could, for example, be syngas derived from coal or gas derived from biomass.

The adiabatic flame temperature of the stoichiometric combustion of methane and oxygen at a pressure of 2.07 MPa, is 3187°C [10]. At this temperature, the Carnot efficiency of a thermodynamic cycle is greater than 90%. No turbines are available that can operate at this high temperature. Therefore, in the gas generator, water is premixed with the natural gas and oxygen before the mixture enters the combustion chamber to limit the combustion temperature. In addition, the gas generator has several sections in which water is added to the combustion products to bring the gas temperature to a level acceptable to available turbines. [11,12] Figure 1 is a schematic diagram of the gas generator. The gas generator was developed by Clean Energy Systems, Inc. (CES), and the technology is described in multiple U.S. and international patents.
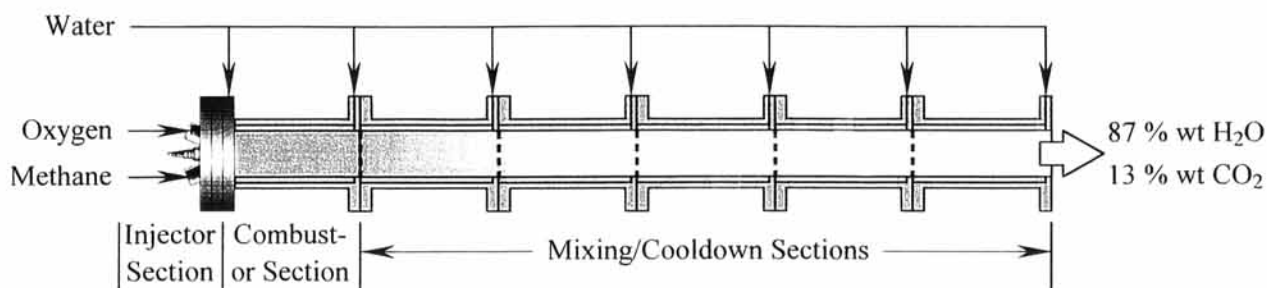


*Figure 1: Schematic diagram of gas generator*

For the purpose of this discussion, we will assume that natural gas consists entirely of methane. The stoichiometric combustion of methane and oxygen produces steam ($H_2O$) and carbon dioxide ($CO_2$). With the addition of water to cool down the combustion products, the gaseous mixture leaving the gas generator consists, by weight, of approximately 83% $H_2O$ and 13% $CO_2$.

Operating pressure of the high-pressure turbine will be 8.3 MPa, the intermediate turbine 0.97 MPa, and the low-pressure turbine 0.12 MPa. Reheat gas generators will be used before the second and the third turbine stages to improve efficiency.

The temperature of the gases entering the three turbines will be 566°C and is governed by the maximum operating temperature of commercially available steam turbines. The overall efficiency of the plant is estimated to be 32%, including power to produce oxygen and to sequester the $CO_2$. Oxygen for the combustion process will be obtained from a cryogenic oxygen plant. Turbine efficiency is assumed to be 90%. Pump and compressor efficiencies are assumed to be 75%. The gases leaving the third turbine will be delivered to a condenser where the $CO_2$ separates from the condensed $H_2O$.

Part of the condensed water will be recycled to the gas generator while another portion will be used in the cooling tower. The $CO_2$ will be pumped from the condenser and compressed to a pressure of 6.8 MPa. The $CO_2$ will then be pumped into the Greenville oil formation, which is located at a subsurface depth of 460 m. The formation covers an area below and adjacent to the Laboratory.

## RESEARCH ELECTRIC POWER PLANT

Figure 2 presents a schematic diagram of the plant. The relatively small size of the plant is a result of the economics of the research. The Laboratory pays $0.03/kWhr for its electricity. Because the output of the plant will be delivered to the Laboratory electrical grid, any electricity produced at a cost higher than this amount would have to be subsidized from the research budget.

To develop the technology of generating electricity without atmospheric exhaust gas emissions in a systematic manner, the plant is being laid out to permit exchange of system components that require development or testing. For example, although the gas generator will have been submitted to tests at a pressure of 8.25 MPa and temperatures ranging from 815°C to 1760°C, these tests are run over a short time frame compared to the typical 20 to 30 year operation of commercial power plants. Hence, one goal of the research is to test the life of the gas generator over a range of operating pressures and temperatures and to study the effects of various starting and shut-down procedures. The stability of the combustion process over a wide range of operating conditions will be evaluated, and the measured performance will be compared with computer calculations of a combustion process in a flowing gas stream. Heat transfer and stress measurements will be made during the various operating conditions.

Special attention will be given to corrosion problems in the design and operation of the plant. Removable corrosion coupons will be installed in the pipes leading to and from major equipment components to study corrosion effects on different materials under plant operating conditions.

The plant is expected to operate at a duty cycle of 50%. A period of three months of operation will be followed by a three-month shut-down period to analyze data obtained from the plant and, if necessary, to make changes in system components and/or measurement instruments.
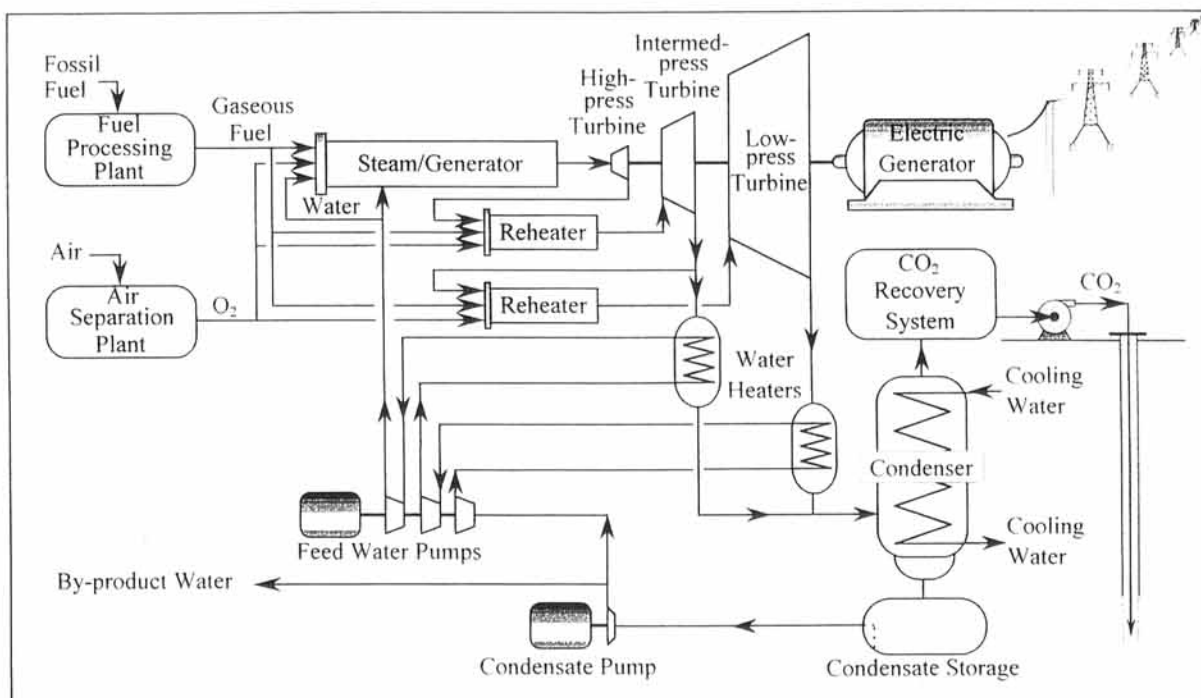


*Figure 2: Schematic diagram of research electric power plant.*

The development and testing of advanced turbines that operate at temperatures higher than the currently available steam turbines is an important aspect of the research. The Laboratory has considerable experience in thermal barrier coatings for high-temperature turbines. The next generation of high-pressure turbines that will operate without blade cooling is expected to operate at a pressure of 10.3 MPa and a temperature of 816°C. Subsequently, the operating temperature of this turbine is expected to reach 980°C. The intermediate-temperature turbine is expected to operate at a temperature of 1425°C in the Phase II upgrade.

Bechtel National Inc. is in the process of making engineering and cost studies of the plant. In one important respect, the research plant differs from a commercial plant in that system components need to be removable for upgrading with new components as the technology is developed.

DOE has funded research to reduce the cost of oxygen generation by means of ceramic membranes. In a future stage of the research, a ceramic membrane oxygen plant will be incorporated in the plant. Similarly, DOE has funded fuel cell research. When these technologies mature and are incorporated into the research plant, efficiencies in the 65-70% range are expected.

The technology described in this paper is believed to be the lowest-cost technology for direct $CO_2$ sequestration. Figure 3 shows sequestration costs in underground formations for various technologies. In this figure, the $CO_2$ is assumed to be pumped to an injection pressure of 34.5 MPa.
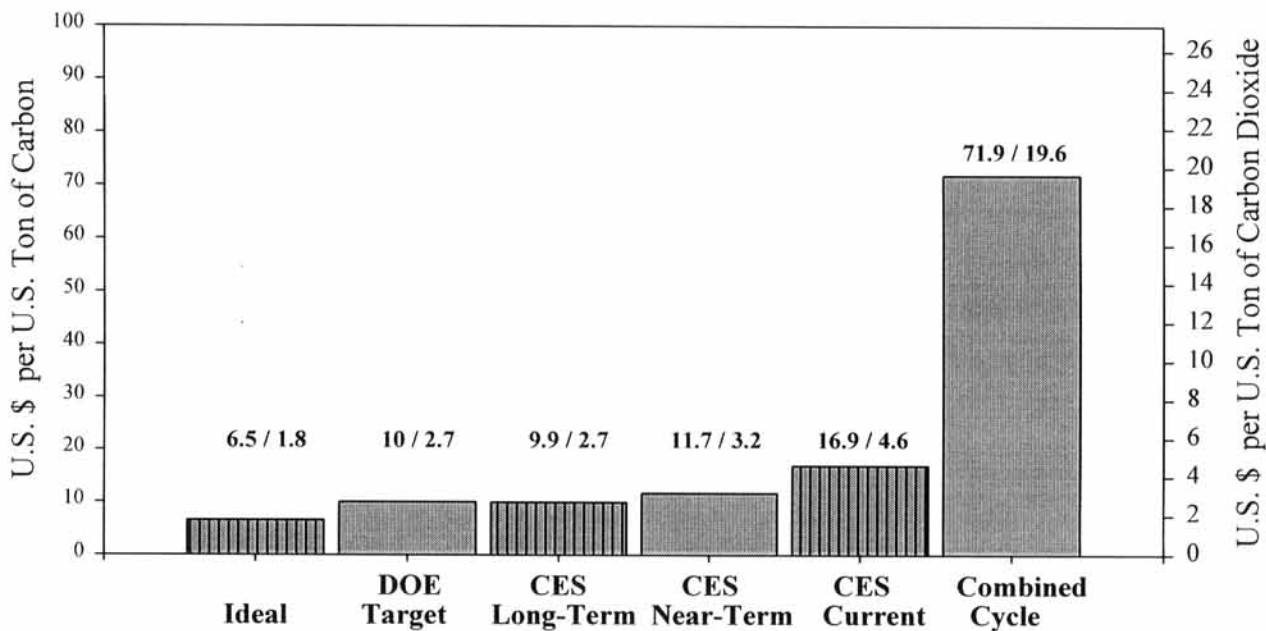


*Sequestration cost includes separating, liquefying and pumping $CO_2$ to 34.5 MPa. Compressor efficiency 80%, liquefaction efficiency 33%. Ideal cost assumes compressor, pump, liquefying and plant thermal efficiencies of 100%; Turbine technology for three turbine stages, I, II, III (pressure, temperature). Current: I (8.3 MPa, 566°C), II (0.97 MPa, 566°C), III (0.12 MPa, 566°C); Near-Term: I (10.3 MPa, 816°C), II (1.14 MPa, 1425°C), III (0.12 MPa, 566°C); Long-Term: I (22.1 MPa, 980°C), II (1.86 MPa, 1760°C), III (0.17 MPa, 980°C)*

*Figure 3: Comparative cost of carbon sequestration for 100 MW plants.*

## CO₂ SEQUESTRATION

The exhaust gases from the plant will be pumped into the Greenville oil-producing formation. The formation is located at a depth of 460 m and extends over an area below and adjacent to the Laboratory. The formation is highly fractured, and the field is in a seismically active zone. Thus, not only will

the research be directed to the study of the effect of $CO_2$ injection on enhanced oil recovery but also on the more general question of the movement of $CO_2$ in a highly fractured formation.

One injection well and four observation wells are planned. Movement of the advancing $CO_2$ front in the Greenville formation will be monitored during the research. Geophysical cross-well imaging measurements such as electrical resistivity tomography and seismic tomography will be made using the observation wells. Time-lapse or repeated measurements and tomographic imaging of the Greenville formation will be used to track the $CO_2$ front. Measurements of near-surface tilting using arrays of bore-hole tilt meters and measurements of down-hole pressure and flow rates will be used in reservoir simulator modeling of the producing formations. The increase in oil recovery due to the injection of $CO_2$ into the Greenville formation will be determined.

The regulatory process to permit pumping $CO_2$ into the Greenville formation is under the authority of the California Division of Oil and Gas. For this case, the permitting process is routine, because $CO_2$ has been used by the oil industry for secondary or tertiary recovery operations for more than forty years. [13]

## CONCLUSIONS

The concept of the described zero-emissions power plant promises high efficiency combined with low-cost $CO_2$ sequestration. The proposed 10-MW research facility will demonstrate zero-emission electricity production using natural gas. The resultant $CO_2$ will be sequestered into a mature oil field.

The new-technology gas generator's long-term operational characteristics and transient response will be determined; advances in oxygen separation and high-temperature steam turbines will be implemented to improve net efficiency. The scientific underpinnings of $CO_2$ sequestration into mature seismically active fields for enhanced oil recovery will be established.

This information, when collected from the proposed 10-MW research facility operations, will provide data necessary to complete reasonable economic analyses for new commercial systems. As the technology develops, syngas derived from coal will be used as a fuel for the plant. The use of syngas in power plants would open the door to making the abundant coal resources of the United States available for power production with zero exhaust-gas emissions to the atmosphere.

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